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Title: Searching for the Decay of Nature's Rarest Isotope: 180mTa

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Report

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Searching for the Decay of Nature's Rarest Isotope: ^{180m}Ta

Sam Meijer

LANL P-1

Ta-180m: Natures Rarest Isotope?

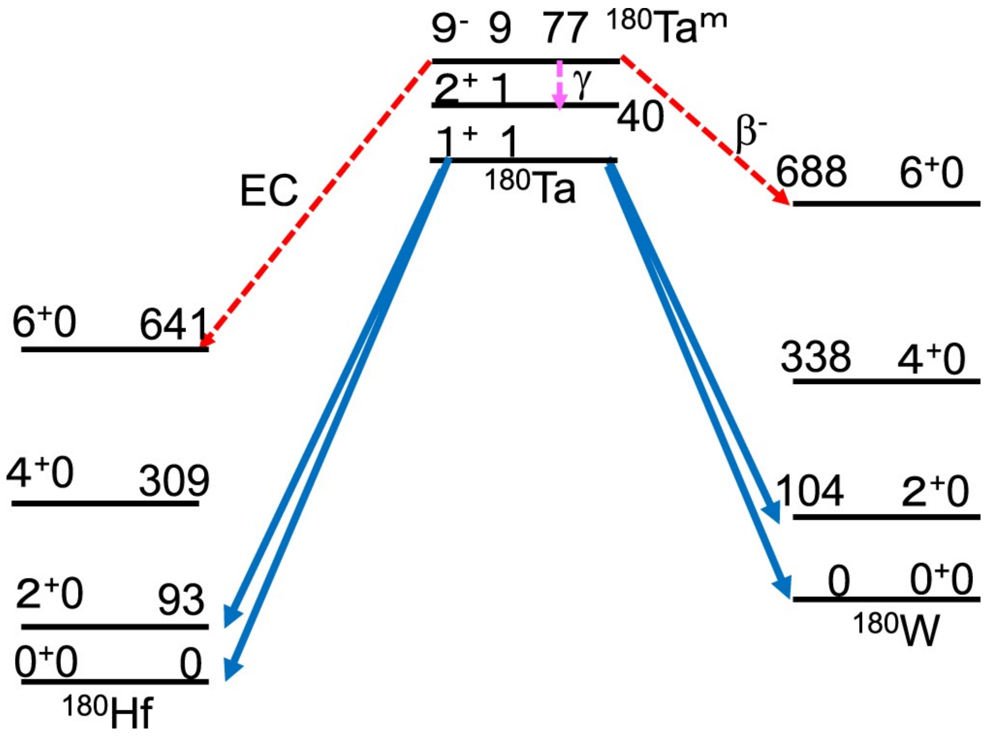
- Naturally occurring:
  - 2 ppm (0.0002%) tantalum in earth's crust
  - Ta-180 is only 0.012% abundant in natural Ta
  - All of the Ta-180 is metastable

Ta^{180m} Motivations

- Fundamental Nuclear Physics
  - The **only** known metastable nuclear decay that has not been observed to decay
- Astrophysics
  - The largest remaining uncertainty for some processes:
    - https://arxiv.org/abs/1907.09178
  - Not totally clear where it comes from:
    - https://arxiv.org/abs/astro-ph/0612427v1
- Possible to detect Dark Matter:
  - https://arxiv.org/abs/1907.00011
- Moonshot applications:
  - Gamma ray laser
  - Nuclear battery

Ta-180m Measurement

- Excited state has spin 9-, ground state is 1+. Only ~77 keV between them.
    - Recently discovered a 2+ ES
- Ground state decays with 8h ½-life
- Isomeric transition is spin forbidden and will be long. The β/EC decays to Hf or W are more tractable.
- Acquiring sufficient ^{180m}Ta isotope is a challenge



https://doi.org/10.1088/1361-6471/aa65f0

Direct Detection of Dark Matter

- Induced de-excitation of the isomeric state due to DM scattering
- Either as:
  - DM is mediator in a scattering process
  - DM absorbed by isomer, exciting to an unstable higher energy state (not exclusive to BSM)
- The lack of a measured decay indicates a limit on the process

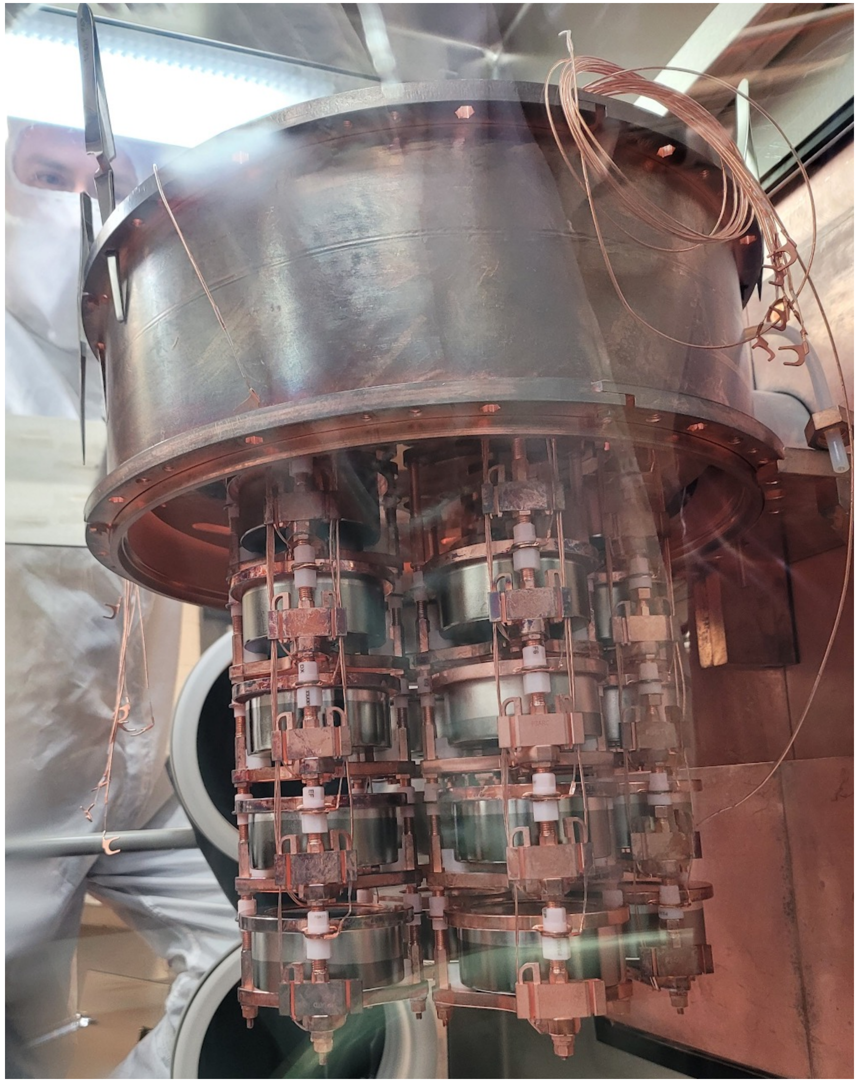
Reaching the necessary sensitivity

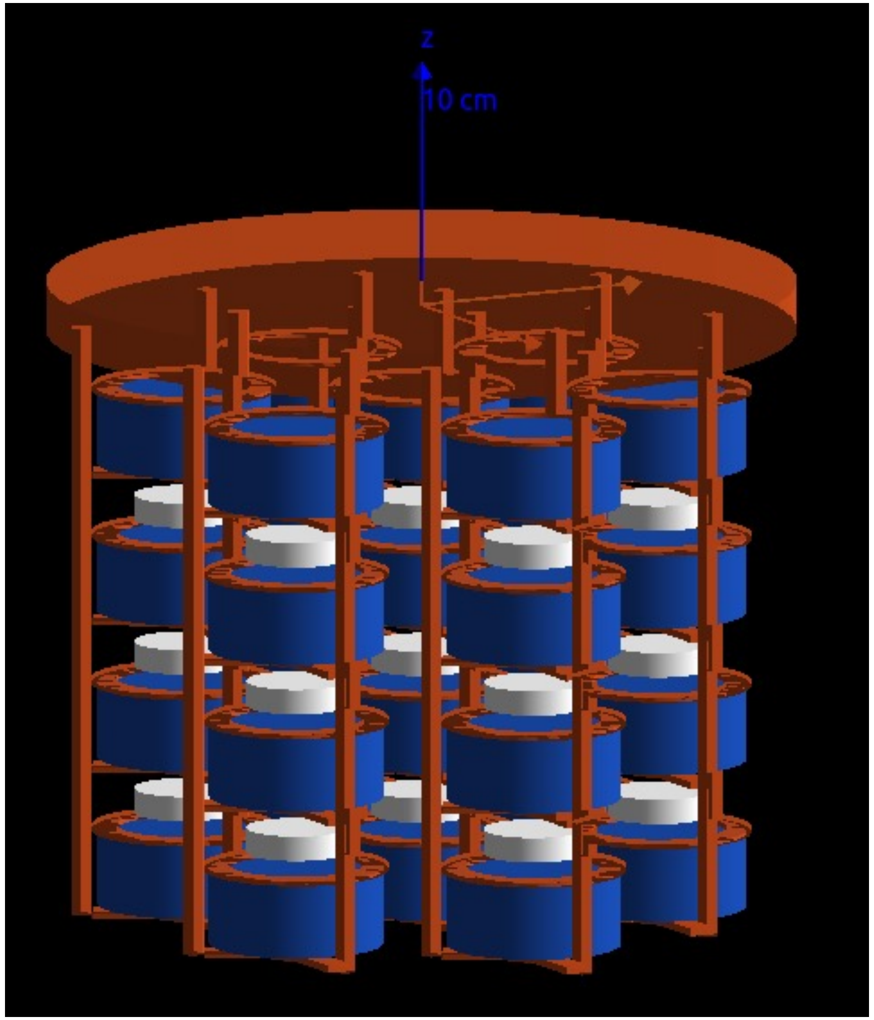
- Just like $0\nu\beta\beta$, it requires:
  - Sample mass
  - Efficiency
  - Low-backgrounds
- Compared to previous experiments, MJD can do:
  - 10x more Ta mass
  - More detectors, higher efficiency for coincidences
  - Lower backgrounds

MAJORANA

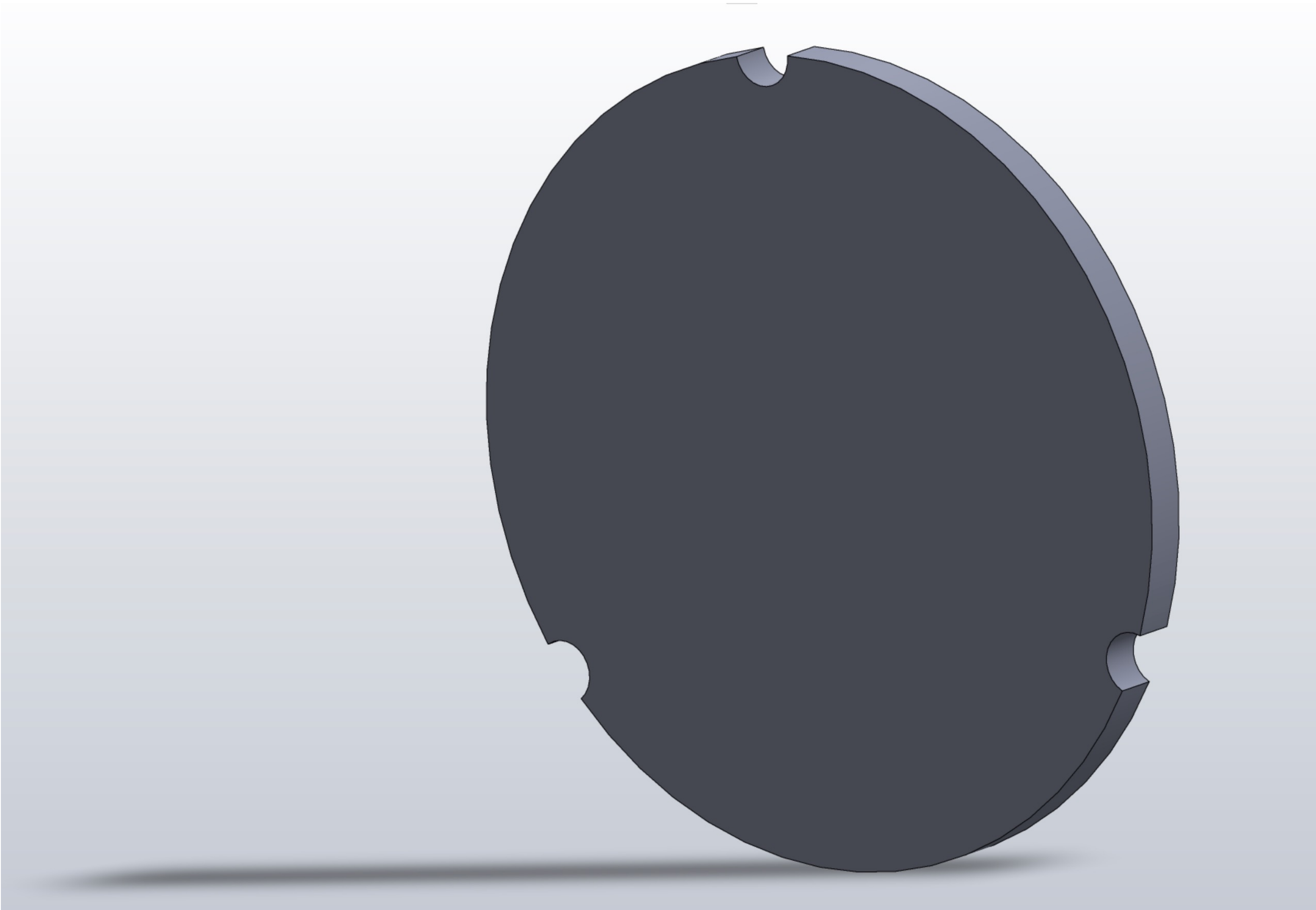
- Array of High-Purity Germanium (HPGe) detectors
- In low-background compact lead shield in underground cleanroom
- Designed for rare event search ($0\nu\beta\beta$)
- Final physics data taking in spring of 2021
- Significant LANL involvement

Tantalum in MJD





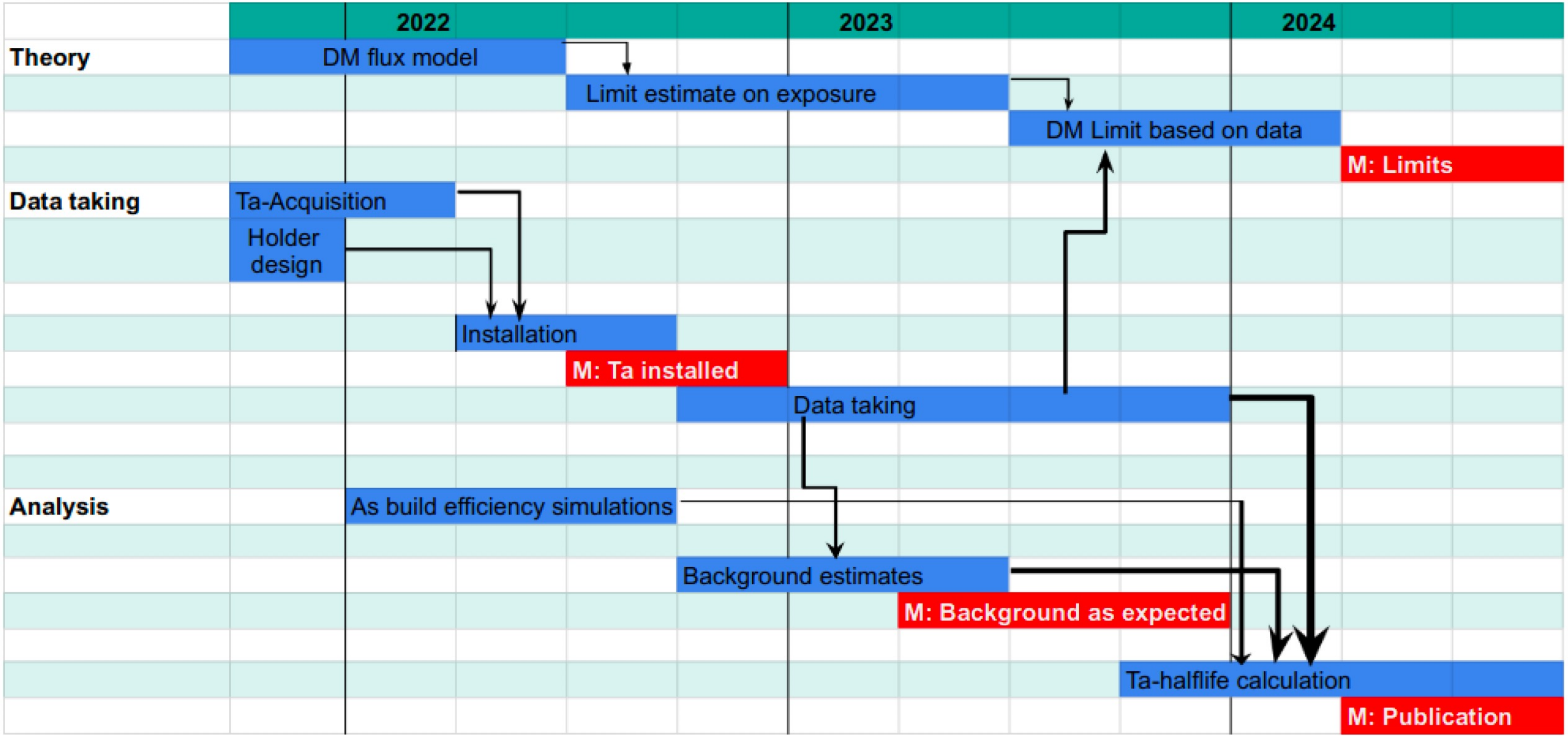
Adding Mass



93.5 mm diameter

Run Plan

- Winter 2021: Design and simulation
- Spring 2022: Acquiring Ta metal components
- Summer 2022: Installing Ta into detector array
- Fall 2022: Take “bg” data for 1+ year


2022
2023
2024
Theory
DM flux model
Limit estimate on exposure
DM Limit based on data
M: Limits
Data taking
Ta-Acquisition
Holder design
Installation
M: Ta installed
Data taking
Analysis
As build efficiency simulations
Background estimates
M: Background as expected
Ta-halflife calculation
M: Publication

Expected Reach

- 2-3 counts/year/detector/keV BG rate
- ~1 keV FWHM energy resolution in 100-300 keV region
- Intrinsic BG of tantalum metal
  - 150 mBq/kg maximum
  - ~mBq/kg more likely
- Leads to BG rate of 3-5 counts/year
- Sensitivity after 1 year:
  - If dirtier**: ~2x$\mathbf{10^{18}}$ yr** (order of magnitude above estimated value)
  - If cleaner: ~**1.6x$\mathbf{10^{19}}$ yr** (50x better than any existing limits)

Conclusions

- As focus switches from MJD to LEGEND, new opportunities arise with the existing detector system
- Ta-180m is an interesting measurement that we hope to finally provide a definitive answer
- We hope for continued collaboration with this group!

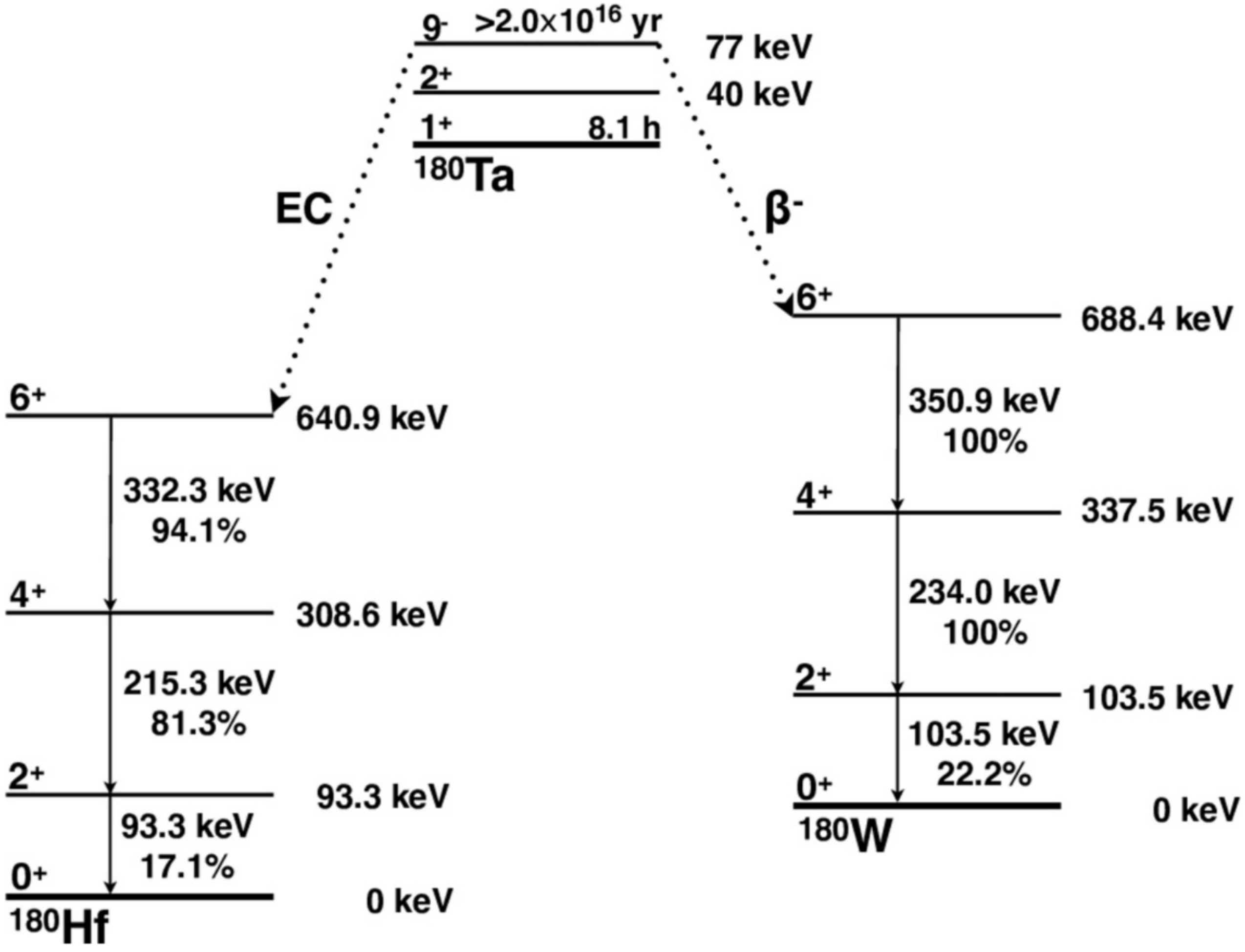
Thanks!

Measurement Signatures

- B decay to ^{180}W
  - Enters at 618 keV level
  - Results in γ cascade:
    - 351 keV
    - 234 keV
    - 104 keV

- EC to ^{180}Hf
  - Enters at 641 keV level
  - Results in γ cascade:
    - 332 keV
    - 215 keV
    - 93 keV

Signatures

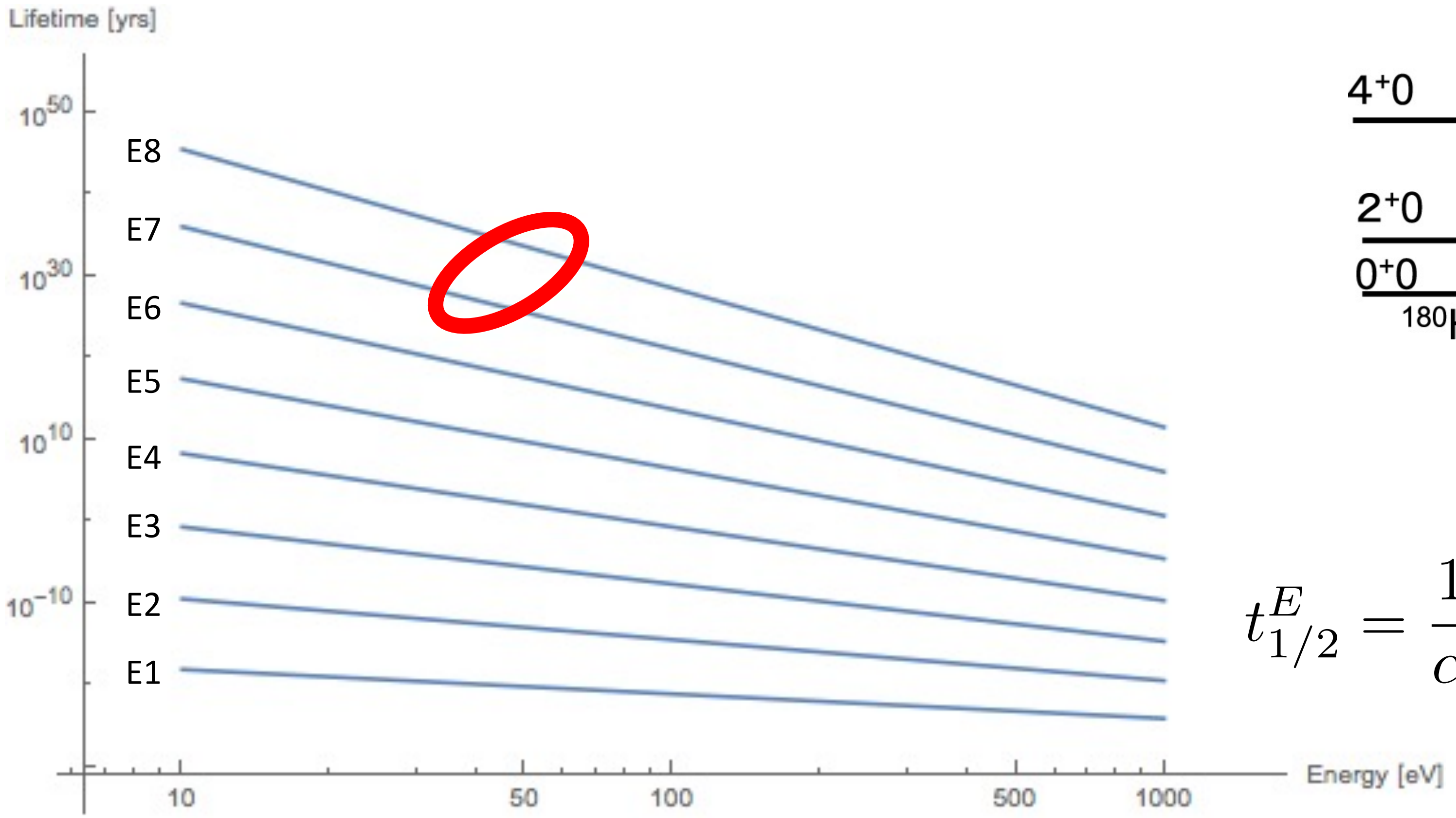


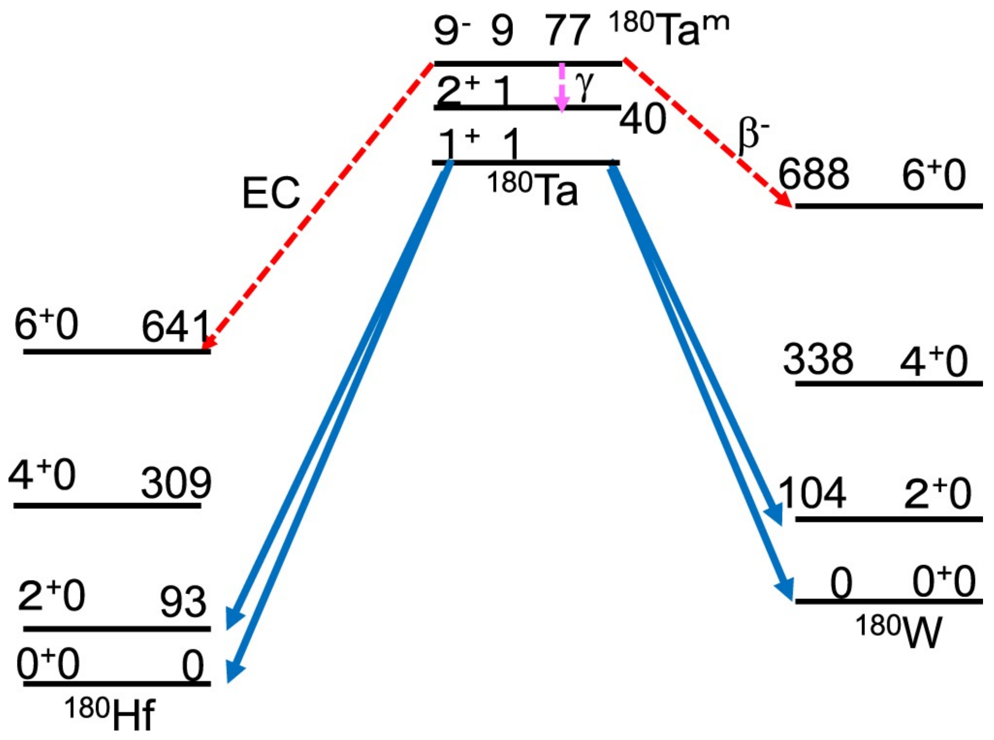
https://doi.org/10.1103/PhysRevC.95.044306

Estimating the Half-Life

- Isomeric transition: $^{180m}Ta \rightarrow {}^{180}Ta + \gamma$

JΠ: 9- 1+





Weisskopf Estimate

$$t_{1/2}^{E} = \frac{1}{\alpha}\frac{\hbar}{E}\left(\frac{E}{hc}\frac{1}{R}\right)^{2l}\frac{l(2l+1)!!}{2(l+1)}\frac{(l+3)^2}{9}.$$

Thankfully there are other options…

- EC and B decays are more manageable:
  - Estimated to be around 10^{18} years
  - Current limits > 10^{17} years